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Pertinent Elements of Critical Thinking and Mathematical Thinking used by Practicing Civil Engineers

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Abstract

Critical thinking and mathematical thinking are inexorably linked and indispensable in solving engineering problems. Therefore, a study to understand how the pertinent elements of critical thinking and mathematical thinking relate and interact in the real-world engineering practice is timely crucial. Unfortunately, there is not much information available explicating about the link. The first part of this paper reports a review on these matters based on rather limited resources. The second part describes a research design to conduct the study in order to understand the interrelation and interaction among the pertinent elements of critical thinking and mathematical thinking. It is followed by a discussion on findings of a pilot study. Insights from the review and the pilot study provide useful information for conducting the main study.

Keywords: critical thinking; engineering education; mathematical thinking; Straussian grounded theory.

1. Introduction

Scholars and practitioners have consensus that teaching of thinking has a distinct value and significance in preparing citizens of the future generation [1].

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In this rapidly changing world, it is seen that knowledge and technology are expanding exponentially. In addition issues and problems such as global warming, pollutions, environments, constructions, economic or political crisis are becoming more challenging, complex and increasingly threatening. Since the information about globalization is readily made available and also changed rapidly, the utilization of such information in making reliable decision is important to be successful in this environment [2]. Consequently, another related issue arises as to whether the current engineering curriculum prepares students with the required critical thinking knowledge, skills and values to face such challenges [3].

Within the context of solving civil engineering problems, engaging critical thinking and mathematical thinking as a two dimensional perspective weaved together, is a way of approaching ABET's engineering criteria. The criteria highlight the required attributes of prospective engineers such as applying mathematical and engineering knowledge, analyzing and interpreting data, formulating and solving engineering problems in engineering contents learning outcomes [4]. Thus, it is deemed relevant and significant to conduct a study to understand the interrelation and interaction of critical thinking and mathematical thinking related to the cognitive activities and aspects of cognition in the civil engineering practices [5]. Therefore, the interaction among pertinent elements of these two types of thinking in the real-world engineering practice needs to be explored, studied and established. This study focuses on civil engineering design practice because it is a practice which liaise to and regarded as an integral to all branches of engineering [6,7]

2. Critical Thinking, Mathematical Thinking and Civil Engineering Design

2.1. Critical Thinking

People live in an increasingly complex and challenging world and thus ability to think critically is very much important in keeping abreast with the changes of the world. Having mental agility and intelligence does not guarantee the ability to think critically. Definitions on critical thinking are produced according to different perspectives. Furthermore, there is still no universal consensus on a definition of critical thinking amongst educators, philosophers and psychologists in the field [8]. Nevertheless, some of the definitions are highlighted for the purpose of discussion and to provide ideas on what critical thinking is. Critical thinking is defined as the ability to apply knowledge and intelligence in making decisions and giving opinions on issues [9]. In accordance with the statement, critical thinking is a mode of thinking; meaning, it improves the quality of thinking about any subjects, contents or problems, by skillfully analyzing, accessing and reconstructing thoughts [10]. Like-mindedly, making good judgment with desirable outcome is the product of thinking process, in agreement with having critical thinking which use those cognitive skills or strategies in increasing the probability of a desirable outcome [11].

It is argued that critical thinking is thinking that has a purpose (proving a point, interpreting what something means, solving a problem) [12] while the national panel of experts in the Delphi Project [13] contend that a critical thinker must have a "critical spirit" which can be viewed as the propensity and inclination to think critically. Critical spirit is collectively a cluster of dispositions, habits of mind, and character traits [14]. In addition, critical thinking is skillful, responsible, thinking that facilitates good judgment based on certain reasons such as; it relies upon criteria, it is self-correcting, and is sensitive to context [15]. Critical thinking is

encompassed in two dimensions, which are the cognitive skills dimension and the affective dimension, namely the dispositional dimension [13]. The cognitive skills are interpretation, analysis, evaluation, inference, explanation and self-regulation. People who are able to think critically will not only apply cognitive skills but also will approach specific problems, questions and issues with critical thinking dispositions such as clarity, orderliness, diligence, reasonableness, care, persistence and precision, which is known as ideal critical thinking. This perspective suggests both dimensions to be mutually reinforced in order to consistently produce useful insights as the basis of a rational and democratic society [12]. Therefore, both dimensions of critical thinking should be explicitly taught and modelled together.

2.2. Mathematical Thinking

In the twenty-first century, everyone can benefit from being able to think mathematically because it is a valuable and powerful way of thinking about things in the world [16]. According to [17], learning to think mathematically means developing a mathematical point of view and developing competence with abstraction, symbolic representation, and symbolic manipulation. Mathematical thinking is important in a larger measure as it equips students with the ability to use mathematics [18]. This is not the same as doing mathematics which usually involves the application of formulas, procedures, and symbolic manipulation. It is argued that mathematical thinking does not have to be about mathematics at all, but parts of mathematics provide the ideal target domain to learn how to think logically, analytically, quantitatively, and with precision [19]. In addition, [17] also mentions that mathematical thinking is not merely involved mathematical content knowledge. The ability to think mathematically and to use mathematical thinking to solve problems is an important goal of schooling in such a way that mathematical thinking will support science, technology, economic life and development in an economy [18].

Mathematical thinking is a process of highly complex activity and is important in three ways; mathematical thinking is an important goal of schooling, mathematical thinking is important as a way of learning mathematics and mathematical thinking is important for teaching mathematics [18]. Whereas [20] sees the importance of mathematical thinking as driving forces to pursue knowledge and skills, and for achieving independent thinking and the ability to learn independently. When the mathematical thinking acts as a drive towards the required knowledge and skills, it cultivates the power to think independently and eventually the ability to learn independently. In the case of arithmetic and mathematics courses, mathematical thinking will be the most central ability required for independent thinking [20]. Mathematical thinking is described by [17,21] as the ability to implement five aspects of cognition namely the knowledge base, problem solving strategies or heuristics, monitoring and control, beliefs and affects and practices.

2.3. Engineering Design

Design is central to engineering. According to ABET, engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to optimally convert resources to meet a stated objective. Among the fundamental elements of the design process is the establishment of objectives and criteria,

synthesis, analysis, construction, testing, and evaluation. The engineering design component of a curriculum must include most of the following features: development of student creativity, use of open-ended problems, development and use of modern design theory and methodology, formulation of design problem statement and specifications, production processes, concurrent engineering design, and detailed system description. Solving a design problem is a process reliant and the solution is subjected to unforeseen complications and changes as it develops [22]. Furthermore, it is essential to include a variety of realistic constraints, such as economic factors, safety, reliability, aesthetics, ethics, and social impact [23]. Therefore, engineering design is a systematic iterative process of converting resources and solving technical problems for the benefit to mankind.

Design is a form of problem solving that is open-ended and complex [24]. Design is the main context for understanding how civil engineers engage in critical and mathematical thinking because it is a practice which liaise to and regarded as an integral to all branches of engineering [6,7]. Moreover, through managing design problems and projects, engineers integrate and apply the content knowledge of mathematics, science and engineering. The design process is a sequence of events and a set of guidelines that takes the designers from visualizing a product to realizing it in a systematic manner [23]. In other words, it is a phenomenon identified through systematic guided changes toward an expected result.

3. Rationale of the Study

Program outcomes listed in the manual of Engineering Accreditation Council for the Board of Engineers of Malaysia [25] emphasize on competency of engineering graduates in dealing with complex engineering problems, critical thinking skills development and evidence-based decision making in the curriculum. It clearly indicates the needs of adaption in cultivating required attributes according to the different disciplines of engineering fundamentals and specialization. Unfortunately, the absence of clear descriptions delineating critical thinking skills for the civil engineering courses and compounded by the varied interests and needs of each university can lead to various ways of expressing the critical thinking skills requirements [26].

Another aspect being emphasized in the engineering program outcomes is the application of mathematical knowledge in the problem analysis and to the solution of complex engineering problems [25]. According to BOK2 ASCE (2008) a technical core of knowledge and breadth of coverage in mathematics, and the ability to apply it to solve engineering problems, are essential skills for civil engineers, in parallel with the fact that all areas of civil engineering rely on mathematics for the performance of quantitative analysis of engineering systems. Therefore, mathematics has a vital role in the fundamental of engineering educations for the 21st century engineers [28,29]. Furthermore, a review into the American Society for Civil Engineering in the body of knowledge reveals that the cognitive level of achievement has been generically described, based on the Bloom's taxonomy and the associated descriptors for the civil engineering courses [27]. However, there are no extensive descriptions delineating critical thinking elements for the engineering mathematics courses. Therefore, to have an empirical insight into the interaction among pertinent elements of critical thinking and mathematical thinking becomes the main goal of this study. In order to be within a reasonable confinement, this study refers to the perspectives of Facione for critical thinking [13,14,15,16] and Schoenfeld for mathematical thinking [17,18].

Moreover, the current scenario to facilitate civil engineering students' learning of engineering mathematics seems to be inadequate in enhancing students' ability to apply the mathematical knowledge and skills analytically and critically. Consequently, it makes the transfer of learning across the students area of study does not occur as efficiently as would have expected [32,33,34,35]. The transfer of knowledge remains problematic and needs to find ways for better integrating mathematics into engineering education [35]. This approach is thought to support mathematical thinking and create the necessary bridge to link mathematics to problem solving in engineering [35]. On top of that, findings from the previous study have shown congruence between critical thinking and mathematical thinking in the civil engineering practice [5]. Therefore, to have insights into the interaction among pertinent elements of critical thinking and mathematical thinking in the real-world engineering practices is thought to be helpful to lubricate and accelerate the process of understanding, applying and transferring mathematical knowledge into engineering education.

4. Exploration: The Path to Walk

4.1. Purpose of the Study

The purpose of this study is to generate a substantive theory pertaining to critical thinking and mathematical thinking. The study seeks to understand the interaction among pertinent elements of these two types of thinking, as perceived by civil engineers in the real-world engineering practice. The ultimate goal from this study is to transform the emergent theory into an integrative diagram or a conditional matrix, as an alternative model that furthers understanding of the interaction among the elements of critical thinking and mathematical thinking. On that purpose, this study aims to answer the main research question about the interaction among pertinent elements of critical thinking and mathematical thinking in the real-world civil engineering practice. This study is based on perspectives and voices of the practicing civil engineers, mainly concerning the civil engineering design context.

4.2. Research Philosophy

In designing a research to be conducted, it is very important to fully understand the philosophical and methodological position, and the methods to be employed, to achieve the research goals [36]. A paradigm says about ontology, epistemology and methodology underpinning the research, is essentially a worldview within which a researcher work, and a whole framework of belief, values and methods within research takes place [37]. Moreover, the research philosophy adopted contains important assumptions about the way in which a researcher view the world and will underpin the research strategy and the chosen method as part of that strategy [38].

An understanding, appreciation and application of multiple paradigms to research are deemed most appropriate in order to have holistic and comprehensive understanding of social phenomenon [39]. In the same context, theoretical paradigms underlying the study of the interaction between mathematical thinking and critical thinking among practicing civil engineers are investigated, interpreted and analyzed under the light of two philosophies, namely interpretive/symbolic interactionism and pragmatism. This philosophical inclination embedded more significantly and seminal in Straussian or Strauss and Corbin's version of grounded theory [40].

4.3. Research Methodology

This study adopts qualitative research method with grounded theory approach. Grounded theory is developed by Glaser & Strauss [41], and is defined as a general methodology for developing theory that is grounded in data systematically gathered and analyzed [42]. Grounded theory is chosen based on the ontological and epistemological beliefs underpinning this research. Grounded theory practices inductive and deductive approaches during the constant comparative analysis. It is known as analytic induction or abduction, which is a product of mental activity and is important in grounded theory method [43, 44]. The logic of abduction allows the researcher to modify or elaborate extent concepts when there is a need to do so, as to achieve a better fit and workability of generated theory [45]. In this iteration of grounded theory process, symbolic interactionism and pragmatism perspectives are much being relied on [46]. Inspired by the evolvement of grounded theory and the appropriateness of answering the research questions in a reasonable confinement, this study employs the Straussian grounded theory methodology [47,48].

4.4. Limitations of the Study

- a) This study is limited to only participants from civil engineering consultancy firms, focusing on civil engineering design process.
- b) Findings from this study are more contextualized to civil engineering design than generalized to other engineering discipline.
- c) This study is also limited to participant willingness to partake in the research study, candor, and capacity to recall and depict their experiences.
- d) All participants who partake in this study are assumed honest in sharing experiences to the best of their memories and remained dispassionate throughout the interview sessions.

4.5. Research Phases

The study is divided into three main phases namely the preliminary study, pilot study and the main study. These phases are designed so as to be able to cover a wide range of study, from the beginning to the end, to judge the feasibility of the study which is a necessary move in a qualitative inquiry [49].

Phase one is a preliminary study, where the sources of data are obtained from preliminary literature review and previous studies. The greatest advantage of having literature at the early stage of the study is to provide examples how grounded theory method has been employed in other research. Those experiences can give input to the study from the methodological rather than substantive position [36]. As grounded theory is an appropriate approach when there is little extant knowledge of the issue, it is considered relevant to have initial review of literature. The purpose is to increase awareness of the existing knowledge base and also to identify gaps, as well as to avoid conceptual and methodological drawbacks [50]. The preliminary literature at the early stage of study is used to enhance the researcher theoretical sensitivity and to be treated as data [36,51]. That is, familiarity with relevant literature can enhance sensitivity in identifying and discriminate data significantly. The concepts derived from the literature can provide a source for making comparisons with data as long as the comparisons

are made at the property and dimensional level, and are not used as data per se [46].

A study conducted by [52] to get an overview of the nature of civil engineering problems and math-related critical thinking skills involved in solving these problems. The study has identified some of the prevalent trends and challenges of civil engineering problems within the real contexts at engineering workplace. Six categories of the themes emerged from the analyzed data includes not well defined problems, non-engineering-oriented parameters, Code of Practice-reliant solution, unanticipated problems, other sectors collaboration and past experiences-dependent solution [52]. From most of categories identified, the use of mathematics was widely applied in solving engineering problems even though quite often it was implicitly embedded. The mathematical thinking was significantly essential, together the critical thinking, were significantly needed to support the analytical ability of civil engineers in interpreting, evaluating, and integrating results. Also, able to increase the quality of making decisions on arguments, in solving civil engineering workplace problems. The findings have been showing a close relationship between critical thinking and mathematical thinking in the process of solving civil engineering problems. This has really driven the researcher to further in-depth investigation into it, to deepen the understanding on: what are pertinent elements of critical thinking and mathematical thinking used by the civil engineers in the real-world practice and how do the pertinent elements interrelate and interact among each other? Therefore, to understand the interaction among the pertinent elements of critical thinking and mathematical thinking is the central aim of this study. Further details of the study are discussed in the remaining parts of this paper.

Phase two is a pilot study where semi-structured interview with a practicing civil engineer was executed based on the purposive sampling method. The purpose of conducting the pilot study was to elicit a bird's eye overview of the real task and nature of work undertaken by a practicing civil engineer [53]. As mentioned by [54], important or salient dimensions in the phenomenon was observed during initial data analysis from the pilot study. The initial information obtained from this pilot interview illuminated the path towards the formulation of the main interview questions. The experiences gained through the interview assisted the researcher in arranging the order of interview questions for the main study.

Phase three is the main study where semi-structured interviews are conducted with practicing civil engineers. Qualitative interview is appropriate when a researcher wants to know how something is happened, or details of the event, or whenever depth of understanding is required [53]. The only plausible way to gather data on how is the interaction among the pertinent elements of critical thinking and mathematical thinking used by the civil engineers is by entering their real engineering world and acquiring their perspectives through in-depth, qualitative interviewing [55]. Hence this research adopts the in-depth semi structured interviews as the primary data collection method. Deriving from the research questions and initial analysis of the pilot interview, an interview protocol that contains questions for the semi structured interviews is formulated. The interview protocol then reviewed and verified by the experts in the related fields. Prior to structuring these main interview questions, the researcher reviewed a reasonably fair reading-up literature about civil engineering procedures, critical thinking and mathematical thinking concepts, in order to increase the theoretical sensitivity. It is important to have a fairly level of understanding of that pertinent knowledge, as it would be beneficial during data collection and analysis process.

4.6. Research Participants

Participants of this study comprise of experts from two civil engineering consultancy firms in southern region of West Malaysia. These firms are chosen because the data needed for this study can be acquired and their nature of work at this place was coherent with the requirements of the intended research. The main targeted participants are practicing and professional civil engineers, who are experienced in civil engineering design for at least five years.

4.7. Sampling

Data collection method is oriented to grounded theory approach, which involves multiple stages of data collection and the refinement and interrelationship of categories of information [56]. Two types of sampling methods involved in this study, namely purposive sampling and theoretical sampling.

In purposive sampling, participants are chosen with characteristics relevant to the study who are thought will be giving rich information to manifest the phenomenon being studied intensely [57]. During sampling, data gathering is not going to be structured too tightly, and the first interviews tend to be very sketchy and awkward, whereas later ones tend to be much richer in data [48]. In this study, the literature review and findings from the preliminary and pilot studies shed lights on how to purposively sample.

If purposive sampling in grounded theory is where to start, theoretical sampling directs where to go [58]. Theoretical sampling is based on the categories of the emerging theory [59] from the evolving concepts/themes derived from data [46]. In doing the theoretical sampling, strategic decision about what or who will provide the most information-rich source of data to meet analytical needs will be determined [36]. This iterative process continues until properties and dimensions of categories under development are saturated with information needed. In addition, writing memos or diagrams are important during this process in order to relate possible sources to sample, to act as repositories of thought in creating an important audit trail of the decision-making process for later use [36,46].

4.8. Data Analysis

Data analysis in grounded theory is a fluid and generative process [46]. The process starts at the moment of initial contact with the phenomenon being studied, beginning with coding activity on the interview transcript and raising it to conceptual level, and it continues throughout the development of a grounded theory. In other words, it is an iterative process where data collection and analysis are concurrent and continual activities [60]. Data are analyzed using constant comparative method, and this comparison method will much rely on the theoretical sensitivity, which is fostered throughout the process [48,60]. Constant comparison involves the constant interplay between the researcher, the data and the developing theory [60]. Therefore, researchers constantly are validating or negating their interpretations while doing the analysis [48]. As the researcher plays an active role in this constant comparison process, having theoretical sensitivity, which is a characteristic of the researcher, involves a mixture of analytic thinking ability, curiosity and creativity [60], is deemed important. The most unique part of data analysis methods in grounded theory is the coding process [60]. The three basic

analytic process involved are called open coding, axial coding and selective coding [47,48,61].

Open coding is the first stage of data analysis, begins after some initial data have been collected, which involves the process of breaking down data, examining, labelling, comparing, conceptualizing and categorizing of the phenomenon as indicated by the data [47,59,60]. During the early phase of open coding, the researcher did a listing, for selecting and relating categories, and for each category, the researcher delineated the properties along with the dimensions. The open coding process provides answer to the first research question regarding the pertinent elements of critical thinking and mathematical thinking used by civil engineers in the real-world practice. Subsequently, the list is extended as the analysis progress which provides the foundation that leads to the logic diagrams done during the axial coding [48]. For this purpose, a research tool, the Conditional Relationship Guide [62,63], is used during the axial coding process.

Axial coding is an intermediate stage of coding process where those deconstructed data during open coding are gathered back together in a new form by creating associations between a category and its subcategories, in which, open coding and axial coding go hand in hand [46,47]. Using the Conditional Relationship Guide in the axial coding process helps the research to visualize the interrelation among the pertinent elements. Generally, axial coding is developing the basis for selective coding [47].

Table 1: Reflective Coding Matrix

| Core Category | Justifying reason mathematically with sense of engineering in making reasonable judgment | | | | | |
|--|--|--|--|--|--|--|
| Processes (action/interaction) | Relating knowledge and experience in examining problems | Forming conjectures and hypothesis in making reasonable conclusions | Having analytical reasoning in making analogy and drawing/sketching diagrams | Confirming, validating and correcting statements | Concerning behavior in making decision along the way | Adapting mathematical engagement and consciousness |
| Properties (characteristic of category) | Contented argument | Reasonable judgment | Evidence-based solution | Sense of engineering | Understanding other's opinion | Proficiency |
| Dimensions (property location on continuum) | Initial scrutiny Well attentive start Experience-based statement | Statement validity Experience-based conclusions Mathematical point of view or sense making | Patterns of problem Reasons Arguments Justifications | Mathematical knowledge Informal/intuitive knowledge Valid statement / reference Correct actions Traceability | Right approach Plan / goal Discussion Distribution Stipulated time | Alternative ways / solutions Flexibility Consideration |
| Contexts | Interpreting <u>Analysing</u> | Evaluating <u>Inferencing</u> Mathematical practices | Solving problems Explaining | Self-reflections Cognitive resources Material resources | Monitoring and control Social resources | Beliefs and affects Truth-seeking |
| Modes for understanding the consequences (process outcome) | Diligence in seeking info | Careful and prudent | Confidence in reasoning | Staying well-informed | Controlled situation | Flexible in considering alternatives |

Selective coding is a process of selecting the core category, which systematically relating it to other categories, and validating those relationships, as well as filling in categories that need further refinement and development [47]. Whereas, the core category is the main theme of the analyzed data and the central phenomenon around

which all the other categories are integrated. This study employs Reflective Coding Matrix [62,63] in the selective coding process to determine the core category. The core category can be described in terms of its properties, processes, dimensions, contexts, and the modes with which its consequences are understood. Ultimately, it is during selective coding that explicating the story line, which is integrating and explaining grounded theory [36,47,60]. An example of Reflective Coding Matrix, as used in the pilot study is shown in Table 1.

5. Discussion

The results of the coding process using Straussian grounded theory analysis for the pilot study are finally presented in the reflective coding matrix. The core category developed during the selective coding process as shown in Table 1, is refined to be Justifying Reason Mathematically with Sense of Engineering in Making Reasonable Judgement. The refined core category depicts a process theory. From this fully developed matrix, the process theory is described as a narrative storyline. The process theory comprises six essential processes: Relating Knowledge and Experience, Forming Conjectures and Hypothesis, Having Analytical Reasoning, Confirming, Validating and Correcting, Concerning Behaviour and Adapting.

In addition, a reflection on the interview conducted during the pilot study highlights several points to ponder before conducting future interviews for main study, as summarized below in Table 2.

Table 2: Summarization of Pilot Study Interview Reflection

| Things to Ponder | | Comments | Justification / Provisional Conclusion |
|------------------|--------------------|--|--|
| Technical | Interview duration | Two-hour interview is considered quite long. Not a problem for interviewing but very time-consuming for transcribing and analysis. | Allowing prolonged engagement - to establish rapport [54]. Proposed duration : 60-75 minutes |
| | Interview location | It's very important to be at a place which is conducive and comfortable to conduct interview. To have clear audio is extremely crucial (provided a good audio-recorder is used). | Meet at scheduled time and place. Ensure no potential background noise. Test the tape, replay, and make adjustment as necessary [54]. |
| Content | By themes | It tends to make the participants feel bored and tired when have to repeat what have been mentioned as different themes may require the same 'story of experience'. | May not proper to ask questions directly about critical thinking and mathematical thinking. To consider more appropriate ways; asking their experiences handling/ managing a |

| | | | |
|--|---------------|--|---|
| | By process | <p>This idea may be good for the study. But, the participants may not feel comfortable as they will not be freely expressing and sharing their experiences, when being too confined with the stages of process.</p> <p>Furthermore, the scope of this study doesn't strictly addressing the data collection against the particular engineering design process.</p> | design project; how and what did they do when handling a complex problem. From there, data of interest will be elicited out through coding process. |
| | By experience | <p>It is like 'putting all the ingredients in a sack, and then have to segregate them separately'.</p> <p>Quite a laborious task to do, but the participants may feel comfortable with it.</p> | |

6. Conclusion

The review has shown the needs to have a study on the pertinent elements of critical thinking and mathematical thinking used by civil engineers in the real-world practice. Therefore, the study aims to answer the research questions regarding pertinent elements used by the practicing civil engineers and to understand the interrelation and interaction among the pertinent elements through grounded theory analysis. This paper draws on the findings and reflection of the pilot study which provides useful information for conducting the main study. Understanding this interaction of pertinent elements of critical thinking and mathematical thinking is contributing useful information to engineering education instructions, which is aligned with the expectations of engineering program outcomes set by the Engineering Accreditation Council.

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